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EXPERIMENTAL STUDY OF ENVIRONMENT AND HEAT TRANSFER IN A ROOM FIRE

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
CENTER FOR FIRE RESEARCH

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I. INTRODUCTION

This final report is written in three sections. The first two draw attention to work reported in detail in the Third Quarterly Progress Report and the third Section describes ongoing work which has not been previously discussed in a Progress Report.

II. DOORWAY MIXING

During the past year we have completed work concerned with mixing, between the two layers within a room, which is caused by the currents flowing into and out of a doorway. The currents in our experiments modeled those that would be produced by a fire of constant heat release rate located within the room. The mixing process was more complex than we had expected and the work discussed in our Progress Report for the Third Quarter may be more closely restricted to the geometry of the room used in the experiments than we would like. However, we believe that the correlation presented in the Third Quarterly Report will give a useful estimate for this mixing process.

This investigation is completed and no further experimental work along these lines is planned for the coming year. We will continue to examine the data and will develop a computer model for use in Room-Fire Codes.

III. FIRE IN CEILING LAYER

The Progress Report for the Third Quarter also included a description of our work, accomplished in the 1983-84 contract period, on the heat release in the ceiling layer when a flame extends far into that layer. The results presented there are not as accurate as we want because our tools for chemical analysis were not accurate enough or complete enough to give us an accurate picture of the chemical composition within the upper layer under the conditions of interest. These problems arose when the fuel air ratio of the gases entering the ceiling layer was above the stoichiometric value. The most serious problems resulted because we did not have the capability of making measurements of hydrogen gas and water vapor concentrations.

In the current year we will continue this work and will have a new instrument, a gas chromatograph, which will allow us to make measurements of all of the principal species. (The major cost of this instrument was supplied by Caltech.) We anticipate that this instrument will allow us to make the accurate determinations of composition required to develop a model for this heat release process. Work in this area will be continued in the current contract year.

IV. GRAVITY CURRENTS - INITIAL FLOW IN A CEILING LAYER

A. INTRODUCTION

We are interested in modeling the initial motion of smoke and hot gas in a hallway or large room when hot gas is introduced into the space either through an opening such as a door or from a fire located within the space.

To have a concrete example in mind consider the development of the ceiling layers produced by a fire in the two-dimensional structure shown in the sketches of Figure 1. The building consists of a small room with an open door which leads to a long hall. The only opening to the outside world is a vent located on the wall of the hall and near the floor.

A fire starts in the small room and smoke rises to form a layer of hot gas near the ceiling, see Figure 1a. Several minutes later, see (1b), when the fire has reached a large size, the hot gas in the room begins to spill out under the door soffit into the adjoining hallway. The rate of flow of the hot gas which enters the hall increases rapidly and quickly rises to a roughly constant value.

The outflowing gas forms a buoyant plume, see (1b), which impinges on the ceiling of the hall and produces a thin wall jet or gravity current which flows at high speed along the ceiling.

The flow in this wall-jet is supercritical, i.e., its velocity is larger than the speed of a gravity wave on the interface between the hot gas and the cooler ambient fluid. The interaction of the head of this current with the ambient fluid produces a hydraulic jump in the supercritical layer, shown in (1c), which entrains a substantial flow of ambient fluid.

The velocity of the gas in the gravity current which forms downstream of the jump is slower than that in the supercritical layer and it contains a larger mass flow rate due to the entrainment process. The current has a definite head and some mixing occurs just behind the head which results in the formation of a mixed region between the current and the ambient flow.

The current formed by this process flows across the ceiling of the hall, see (1c and 1d), with a constant velocity and depth. The mass flow rate and depth of fluid at a point just downstream of the jump are fixed by the properties of the jump, the conditions in the flow upstream of the jump, and the properties of the gravity current formed by the jump.

A short time later, the front of this current impinges on the far wall of the hall, (1e), and reflects as a group of waves on the interface which propagate back toward the jump, (1f). Mixing occurs during the impingement process but the reflected waves do not break and hence do not cause any further entrainment of ambient fluid into the current. When the waves reach the hydraulic jump located near the left hand side of the hall, the jump is submerged in the hot gas, (1g), and no further entrainment of ambient fluid occurs there.

After several reflections, the wave train dies out and a uniform ceiling layer is produced in the hall. The layer slowly grows deeper as the hot gas continues to be supplied to the hall from the fire room.

Heat transfer from the hot gas to the wall occurs throughout this flow by a convective heat transfer process. The magnitude of the heat transfer rate will affect the motion of the current, since the buoyancy of the flow will be reduced.

During the process described above, the pressure within the two rooms will rise due to the the addition of heat and the production of hot gas by the fire. This pressure rise will cause a flow of ambient fluid out of the vent and will set up a velocity field in the ambient fluid remaining in the two rooms. Other motion in the ambient fluid is caused by the passage of the gravity current down the hall. Although the velocities in the ambient fluid are usually small, under some circumstances they may have important effects on the motion of the current due to the development of a boundary layer on the ceiling in front of the head of the current.

The flow described above contains many of the novel features which we wish to examine in this research program. Those which do not fit neatly into the two-layer fire models are the three-dimensional and unsteady geometry of the current, the entrainment in the hydraulic jump, and the mass loss into the mixing region at the head of the current. Heat transfer associated with the motion of the current will affect each of these processes. However, once the initial hydraulic jump is submerged, the layer of hot gas within the hall has approximately a uniform depth and density, and can be treated by the simple two-layer model.

Entrainment at the hydraulic jump can be important. The total mass entrained into the current depends on the entrainment rate at the hydraulic jump and on the period during which it will act. The period is fixed by the geometry of the room, and the velocity of the front of the current and of the reflected waves which eventually submerge the jump. These features must be included in any accurate model of the flow.

Finally, there are situations in which the motion of the layer could be important. For example, if the gravity current is deep enough to submerge an automatic sprinkler head, the motion of the front will determine when the sprinkler can be set off. Or, if the vent on the right hand wall of Figure 1 had been located at ceiling level, the motion of the front will determine the time at which smoke would first leave the hall.

To summarize, the use of the simple two layer model to describe this flow is inappropriate because the layer thickness is not uniform in the hall, because considerable mass may be exchanged between the hot and cooler fluid due to entrainment at the jump and at the head of the gravity current, and because heat transfer from the layer to the wall depends on and influences the motion of the front. In rooms with a height to length ratio of 1 or 2, these effects are usually small enough and are completed in so short a time that they can be ignored. However, in a space such as a long hallway or large room, for which the length to height ratios can be 20 to 50, the time required for the development of the ceiling layer may be long compared with other processes of interest and the effects of heat transfer, and entrainment may not be minor.

The features of the flow which must be included in a fire-model are:

(1) the rate of spread of the gravity current in a variety of geometric configurations and for a range of Reynolds numbers, and the

corresponding motion of reflected waves which eventually submerge the jump,

(2) the geometry of the current while it is spreading throughout the space,

(3) the exchange (in both directions) of material between the current and the cooler ambient fluid which may occur at the head of the current, at any hydraulic jumps which occur in the flow, and at the impact of the head on a side wall, and

(4) the heat transfer from the current to the ceiling during the whole history of the fire and the influence of this heat transfer on the other three processes.

The aim of the present research work is to obtain a good physical understanding of these features of the flow and to develop an analytic model for application in multi-room fire codes.

A considerable body of information concerning items 1 and 2 is available for adiabatic conditions and for flows in simple two-dimensional and axisymmetric geometries. This information will be reviewed in Section IV B. In this review, we will restrict our attention to the motion of the front of a gravity current such as that illustrated in Figures 1c and 1d, and also in Figure 2, and will discuss the initial hydraulic jump, shown in Figures 1c to 1f, and other features of the flow in a later report.

Little data are available for more complex geometric conditions of interest to us and less, concerning the effects of mixing and heat transfer. An experimental program has been started to investigate these problem areas and it will be described in Sections IV C and D. This program has two parts: in the first, salt-water/water modeling techniques are being used to study the effects of geometry and Reynolds number on the flow. This part of the experimental program and preliminary experimental results are presented in Section IV C.

An important part of our experimental work will be to obtain data for non-adiabatic flows in which heat and mass transfer from the gravity flow may substantially affect the flow. Experiments, which make use of hot air currents, have been started to investigate these processes and they are described here in Section IV D.

B. REVIEW OF INFORMATION CONCERNING GRAVITY CURRENTS

A body of experimental and theoretical work is available concerning gravity currents moving over horizontal surfaces because of interest in flows such as those present in estuaries, where salt water from the ocean flows upstream under fresh water outflowing from a river, in cooling water outfall flows from power plants, where hot water discharged from a power plant flows out over cooler river or ocean water, and in the atmosphere, where cold fronts may intrude beneath warmer air.

This work is reviewed by J. E. Simpson (1982) and two of the key papers mentioned in this review are Benjamin (1968) and Simpson and Britter (1979). A third paper by Wilkinson (1982) contains an important addition to our understanding of these flows. Other important papers are included in the reference list.

Much of the information in these papers may not be directly applicable to our problems because, the effects of heat transfer between the intruding gravity current and the wall have usually been ignored, and because the boundary conditions on the flow of the ambient fluid may be different in our case than in those studied previously. The most commonly investigated flow is one in which the fluid which forms the gravity current is injected from the same end of the corridor as that from which ambient fluid, displaced by the current, is withdrawn. Other boundary conditions for the withdrawal of the ambient fluid can be easily modeled in an inviscid flow by making a Galilean transformation.

However, in a real fluid, viscous effects will change the velocity profile near the wall and have been observed to have a large effect on the geometry and velocity of the current. Clearly, the simple Galilean transformation will not allow us to account for these effects.

Finally, the work by Simpson and Britter involved measurements made on the head of a gravity current in which head of the current is held fixed and for which the distance from the source to the head was very small. These data do not give a complete picture of the motion of the front when the front has moved out a large distance from the source because the effects of viscosity on the current are not present in their experimental work.

Thus, there may be substantial quantitative differences between modeling results and the motion of full scale gravity currents produced by fires but large qualitative differences are not expected.

1. Classification of Inviscid Flows

Many types of flow can be produced when hot gas is introduced into a room or hallway and several of these are illustrated in Figure 1. In this report we will concentrate on the flow in the gravity current illustrated in Figures 1c,and 1d, and in more detail in Figure 2.

The exact nature of the flow will depend strongly on parameters of the flow as well as the boundary conditions. For example, mixing and entrainment between the injected flow and the ambient fluid will be controlled in part by the Froude number of the current when it enters the hall. Viscous effects will be important when the Reynolds number for the flow are small enough or when the current moves far enough down the hallway that the effects of boundary and mixing layers become important, and the end of the hall used to withdraw the ambient fluid displaced by the current will also influence the flow field.

We will describe a few special cases of these flows in a general manner and then will concentrate on the most simple. The nomenclature used here to describe the flows is based on the analysis discussed in the following section but the observations are based largely on flows of salt water moving into ducts filled with fresh water.

(i) Subcritical Source

As an example of the problems we wish to study, consider the inviscid flow illustrated in Figure 2 which is produced when a steady stream of hot gas is introduced at one end of a long hallway at time zero and an equal volumetric flow of the ambient fluid is withdrawn from the same end of the hall. The material is injected so that we can ignore mixing at the inlet between the hot gas and the cooler air present in the hall.

With a subcritical source, the gravity current forms a thin layer which moves away from the source with a constant velocity and with a well defined front. The flow described here is similar to that described in Figure 1 in the region to the right of the hydraulic jump except that the boundary condition on the ambient flow is different.

This source is equivalent to the subcritical flow encountered in open channel flows of water in which the Froude number is less than one and for which sudden changes in the depth of the flow are not possible. However, the flow is more complex here because two streams are involved, the gravity current and the return flow in the lower layer. These differences will be discussed below.

Mixing between the current and the ambient flow occurs in a hydraulic jump associated with the supercritical flow of material in the lighter ambient fluid and, depending on the flow rates, this jump may occur either just behind the head of the current, as is suggested in Figure 2, or closer to the source as shown in Figures 1 and 4.

In the hydraulic jump, material is entrained from the gravity current into the ambient flow and this process produces a mixed layer between the current and the ambient fluid which is primarily made up of ambient fluid. The bottom of this layer is roughly level with the bottom of the head of the current as is suggested in the sketch. Little mixing occurs in the shear layer which forms between the current and the ambient fluid.

Viscous effects produce a boundary layer between the current and the wall, and a shear layer between the lower edge of this current and the ambient fluid. When the thickness of these layers becomes appreciable compared to that of the current, they will affect the flow. In addition, when the Reynolds number for the flow is small, viscous effects can have a large influence on the flow at the nose of the front and will cause a substantial reduction in the speed of the front. For very small Reynolds numbers, the head of the current disappears entirely.

We can identify three regimes of flow here: an inertial regime in which the effects of viscosity are small; a very low Reynolds number regime in which viscous effects dominate the whole flow and in particular the head of the current; and an intermediate viscous regime in which the development of boundary and shear layers affects the flow. In the latter regime, the velocity of the front and the thickness of the layer behind the head decrease with increasing distance from the source, e.g., see the review in Chen (1980), and other material in Chen and List (1976) and Didden and Maxworthy (1982). The viscous regime will always be reached if the flow is allowed to propagate far enough from the source.

(ii) Supercritical source:

From an analogy with open channel flows, we expect that, when the Froude number of the source is greater than one, rapid changes in the depth of the current are possible and that changes in depth will occur through a process similar to that which occurs in a hydraulic jump such as that shown in Figures 1 and 3.

In the present flow, the hydraulic jump will be accompanied by entrainment of ambient fluid into the gravity current because the fluids are miscible. Downstream of the jump, the depth of the current will be greater than at the start; there will be a smooth change in the velocity and density profiles from the ambient values at the lower edge of the current to larger velocities and smaller densities at the wall; and the average Froude number will be less than one. In addition, the mass flow and density in the current will be increased by entrainment of ambient fluid at the jump. The jump process has been examined experimentally by D. L. Wilkinson and I. R. Wood (1971).

For the situation shown in Figure 1, the strength of the jump is determined by a coupling between the jump process and the motion of the gravity current which it produces. We will discuss the modeling of this process in a later Report.

The entrainment of ambient fluid into the current at the hydraulic jump also causes a return flow in the ambient fluid. When the inlet flow rate is increased still further, this return flow can cause a gross mixing between the current and the ambient fluid. This mixing and the recirculation of the hot gas can lead to the more complex flow field sketched in Figure 3b in which the hot gas from the fire is entrained into the recirculating flow which feeds the jump.

(iii) Plume source:

Finally, when the source of the hot gas is a plume from a fire, flows may be produced which behave like any one of those discussed above. Experiments are required to determine which will occur under a given set of circumstances. The sketch of Figure 3c illustrates one of these flows and other possibilities are described in Lee, Jirka and

Harleman (1974).

Our initial experiments will be concentrated on the subcritical flow of Figure 2, for which no mixing occurs due to the injection of the gravity current into the hall. The more complex cases will be examined later and will not be discussed further in this report.

We turn now to examine in detail the gravity current produced by a subcritical source in an inviscid flow.

2. Description of Subcritical Gravity Currents

The theoretical problem is most conveniently posed as follows: Given the flow of a light fluid into a two-dimensional rectangular channel filled with an initially stationary ambient fluid, whose density is greater than that of the injected fluid, find the velocity and shape of the current produced in the duct when the displaced heavy fluid is withdrawn from the end of the duct used to supply the lighter material.

Benjamin (1968) has analyzed a simplified version of the gravity current under a set of assumptions which makes the flow resemble a gravity current in the inertial regime. The effects of viscosity, mixing, and breaking waves observed at the head of the current are ignored. However, he does include losses as a parameter, and determines the depth of the current and the velocity of the front in terms of this parameter. The loss mechanism is not discussed and is not included in the physical picture of the model.

In a later paper, Wilkinson (1982) clarified the model of Benjamin (1968) by investigating in detail the loss mechanism. He was interested in flow of air into a channel filled with water. Because no mixing can occur between these two fluids and because viscous effects are often negligible in the air, this flow is particularly well modeled by the calculation. In the model used by Wilkinson, losses are allowed to occur in a bore or hydraulic jump which is assumed to lie between the head of the current and the source. The flow is assumed to be energy conserving except for the bore and the affects of mixing at the head and of viscosity throughout the flow are ignored.

In the following paragraphs, the analysis of Wilkinson is used to discuss the idealized flow shown in Figure 4.

Both Wilkinson and Benjamin investigated gravity currents which move into an initially quiescent fluid and we will restrict our analysis to this case too. However, under some circumstances, the development of a boundary layer on the wall upstream of the current can have a large effect on the shape of the head of the current and on its velocity.

(i) Constant Energy Flow

To illustrate the different flow subcritical flow regimes, we first examine the flow produced when a closed duct, initially filled with a heavy fluid, is opened at one end and a lighter fluid which surrounds the duct is allowed to replace the heavier fluid. This replacement occurs when the heavier fluid flows out of the bottom side of the open end and the lighter fluid flows into the top. This process, has been investigated experimentally by Zukoski (1966) and is illustrated in Figure 4a.

Benjamin (1968) showed that only one depth is allowed for the current when the energy in the flow is conserved. For this constant energy case, see Figure 4a, the current occupies the top half of the duct, and the flow in the lower layer is critical with respect to a coordinate system fixed in the duct wall. This limiting case is called the Constant Energy regime.

(ii) Non-steady Flow Regime

We next consider the flow described above except that now the downstream end of the duct has been slightly blocked on the bottom side. A bore is produced in the outflowing stream by this obstacle which intrudes into the critical flow of the heavier fluid. The bore propagates upstream from the blockage with a velocity which depends on the depth of the fluid, the density ratio, and the velocity in the lower layer upstream of the bore.

For small blockage, Wilkinson shows that the bore moves upstream with a lower speed than the front. Consequently, it can not catch up with the front and the resulting flow is unsteady. The motion in this regime is shown in the sketches of Figure 4b and 4c. In this regime, because the bore moves slower than the front, the motion of the front is unaffected by the bore and the velocity of the front has the same value it had in the flow described above in (i). The depth of the current in the constant energy region behind the head is still half of the duct height. However, the current depth is reduced by the bore and, consequently, the volume flow rate of material in the current is less for this case than that in the constant energy regime.

The presence of the bore is a modification suggested by Wilkinson (1982). This regime is called the Unsteady Flow regime because the distance between the bore and the front increases with time.

(iii) Steady Flow Regime

The depth of the layer of ambient fluid downstream of the blockage, h2, and, consequently, the speed of the bore, v , increase as the blockage is increased. When the depth of the layer rises to about 78% of the duct height, Wilkinson (1982) shows that speed of the bore becomes equal to the speed of the front and for any deeper current the bore is able to catch up with the front. This leads to the formation of a steady flow, shown in Figure 4d, in which the front and the bore move as a unit and with a constant velocity. In this regime, the depth of the current, the volumetric flow rate of lighter material and the velocity of the front decrease as the blockage is increased.

This Steady Flow regime is identical to that described by Benjamin (1968) with the exception that Wilkinson has included an explicit description of the loss mechanism.

(iv) Coflowing Ambient Stream

In the above flow regimes, we assumed that the velocity of the more dense fluid upstream of the front was zero. Because we are dealing here with an inviscid approximation, we can relax this condition by using a Galilean transformation in which the coordinate axis is translated parallel to the duct wall with a constant velocity. This technique will allow us to describe the flow field when we impose any velocity we choose on the flow upstream of the front.

However, in an experimental situation, the flow is viscous, and this procedure can lead to an incorrect prediction of the flow field due to boundary layer effects on the head of the current.

3. Analytic Description of Subcritical Sources

Consider the flows shown in the sketches of Figure 4 and the notation defined there. We assume that flows in the gravity current and the ambient fluid are uniform and parallel to the walls except near the front of the current and the hydraulic jump. We will assume that the fluids are incompressible because, in the fire situation of interest to us, the pressure will remain so close to atmospheric that the density of the gas will not be affected by changes in it. Of course, density variations due to temperature are allowed.

Mass transfer at hydraulic jumps is not allowed and the velocity far upstream of the current is zero.

The flow rate per unit width and density of the light fluid in the current are u and ρ, and the density of the heavier fluid is ρ_a. In the following discussion, velocities are given in the coordinate system fixed in the wall of the duct and in defining dimensionless parameters, absolute values of the velocities are used.

In general, the volumetric flow rate per unit width supplied by the source is given by continuity argument as the product of the velocity in the current v and the depth of the current h, evaluated near the source, or

$$u = vh = v(ho-h2), \qquad (1)$$

where ho and h2 are the depth of the duct and depth of the ambient fluid near the source. Thus, either v or h can be taken as unknown when u is specified.

The velocity in the current beneath the source, v2, must be large enough to withdraw a volumetric flow rate from the duct equal to that of the source because we have assumed that no flow occurs in the duct far upstream of the front. Then,

$$v2 = vh/(ho-h) = u/(h2)$$

or

$$F2 = v2/\sqrt{g'ho} = U/H2$$

where

$$H2 = h2/ho \quad \text{amd} \quad U = u/\sqrt{g'ho^3}$$

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To simplify the algebra of the problem, the ratio h2/ho defined as H2 is used as one of the independent variables for the problem and we will solve for a dimensionless value of u defined above as U rather than use u as the independent variable which it often will be in experimental work.

(i) Constant Energy Flow

In this limiting case, Benjamin (1968) showed theoretically that the layer thickness h is half of the duct height and that this is the maximum value for the layer thickness which is possible . Thus,

$$h1 = h2 = h)max = (1/2)ho$$

or if we use capital letters to denote dimensionless parameters,

$$H2 = h2/ho = 1/2 \qquad (2)$$

In this case, the velocity of the front and that of the fluid in the current are equal and are:

$$vf = v = 1/2 \sqrt{g'ho} \qquad (3)$$

This is the maximum velocity that the current can have. The Froude number for the front and the current are defined as:

$$Ff = F = v/\sqrt{g'ho} = 1/2 \qquad (4)$$

The volumetric flow rate per unit width also takes on a maximum for this case. It is given by:

$$u = u)max = 1/4 \sqrt{g'ho^3} \qquad (5)$$

and the dimensionless value is

$$U = u/\sqrt{g'ho^3} = 1/4 \qquad (6)$$

for the Constant Energy regime.

(ii) Unsteady Flow Regime

In this regime, Wilkinson (1982) showed that the region near the front of the current behaves exactly like the constant energy flow described above. The dimensionless velocity of the front and depth of the current in this region are still given by equations 2 and 4, and the velocity of the bore vb was found to be less than that of the front.

The Froude number for the bore can be written in terms of H2 as

$$Fb = vb/\sqrt{g'ho} = \{((1/2)H2(2H2 + 1))^{1/2} -1/2\} \qquad (8)$$

and the volumetric flow rate at the source, is found by a continuity argument to be

$$U = u/\sqrt{g'ho^3} = 1/4 - Fb(H2 - 1/2) \qquad (9)$$

From Equation 1, the velocity in the current near the source is

$$v = u/(1-H2)ho$$

or (10)

$$F = v/\sqrt{g'ho} = (U)/(1-H2)$$

(iii) Steady Flow regime

In this regime, the bore moves with a higher velocity than the front and catches up with the head of the current. A steady flow is produced which is identical to that analyzed by Benjamin (1966).

The flow parameters of interest can be obtained from the equations:

$$F = Ff = Fb = v/\sqrt{g'ho} = (H2(1-H2^2)/(2-H2))^{1/2} \quad (11)$$

Using the continuity of flow, equation 1, we find that:

$$U = F(1-H2) \quad (12)$$

Thus, given a value for H2, we can find F and U or conversely, given U we can find F and H or H2.

Finally, consider the limiting flow as ho becomes very large compared with the depth of the current, h. Examination of equation (11) shows that in limit when the layer thickness h is held constant and ho becomes very large:

$$v)o = \sqrt{2g'h}$$

(13)

$$u)o = \sqrt{2g'h^3}$$

For most fire problems, this limit will not be interesting but it does give a limiting value for the velocity of the front.

(iv) Numerical Results for Standard Boundary Conditions

Numerical results for the problem described above are given in Table 1 and Figure 5 where values of U, Ff, Fb and H are presented as functions of H2. In addition, the value for the velocity of the current, normalized of $\sqrt{g'h}$ is given as V in this table. For a given problem, if we assume that values are given for the reduced gravitational acceleration g', the duct height ho, and volumetric flow rate u, then values of U can be calculated and used to obtain values for the other dimensionless and dimensional parameters of the system. Examples will be given in the next section.

(v) Coflowing Ambient Stream

We are interested here in examining a variation on the problem discussed above which involves the relaxation of the condition that the fluid velocity upstream of the front is zero. For example, a second interesting limit is to require that ambient fluid enters the lower layer at the source end of the duct with an arbitrary velocity, $v2'$, which can take on positive or negative values. See Figure 6.

For the standard solution, the boundary condition applied to the problem was that the fluid velocity far upstream of the head of the front was zero. The velocity in the flow beneath the source is fixed by the continuity equation and is

$$v2 = -\ v(ho-h2)/h2 = -\ u/h2 \tag{14}$$

If we ignore the effects of viscosity, we can solve for the velocities of the source, bore and front in the new system by making a Galilean transformation which makes the value of the velocity in the ambient fluid beneath the source equal to an arbitrary value, say $v2'$. We will use primes to distinguish the solutions for this second problem from the solutions to the standard problem.

If the origin for the y axis, shown in Figure 6a for the standard solution, is translated to the left with a constant velocity equal to $(v2' + u/h2)$, the velocity of the ambient fluid seen by an observer in this new coordinate system, see Figure 6b, will be $v2'$. Of course, the geometry of the flow will be unaffected by this transformation and, for example, $h = h'$.

To obtain the velocities in this new coordinate system we must add the quantity, $(v2' + u/h2)$ to each of the velocities obtained for the standard problem. The results are summarized in Table 2:

TABLE 2: ARBITRARY VALUE FOR V2′ OR F2′

Parameters for:	Constant Energy	Unsteady Flow	Steady Flow
$F' = v'/\sqrt{g'ho}$	$1.0 + F2'$	$F/H2 + F2'$	$F/H2 + F2'$
$Ff' = vf'/\sqrt{g'ho}$	$1.0 + F2'$	$Ff + F2' + F(1-H2)/H2$	$F/H2 + F2'$
$Fb' = vb'/\sqrt{g'ho}$	---	$Fb + F2' + F(1-H2)/H2$	---
$U' = u'/\sqrt{gho^3}$	$U/H2 + (1-H2)F2'$	for all regimes	

Here, $F2' = v2'/\sqrt{g'ho}$ is specified.

In this table, we use a prime to denote the velocities in the coordinate system in which the ambient velocity beneath the source is $v2'$ and the unprimed quantities are those obtained in the standard problem and with numerical values listed in Table 1.

As an example for the application of these results, let the velocity $v2'$ be zero, and select values for g' and ho. Then $F2'$ is zero, and when we pick a value for u, we can immediately obtain values for U and, consequently, all the unprimed parameters from Table 1. Then using Table 2, the primed quantities can be found. If we use a more reasonable definition for the problem and select a value for u' rather than u, an iterative method must be used to find the appropriate value for U and U'.

Numerical Values for the primed quantities are shown in Table 3 for the special case that the velocity in the ambient stream at the origin is zero, i.e., for F2′=0. Values for the standard problem are also given in this table for purposes of comparison.

TABLE 3. Parameters for F2′=0

H2 h2/ho	U $u/\sqrt{g'ho^3}$	U′ $u'/\sqrt{g'ho^3}$	Ff′ $vf'/\sqrt{g'ho}$	U′/U vf′/vf	$\left(\frac{vf'-vf}{vf}\right)$
0.98	.0039	.0040	199	1.020	.020
0.94	.0193	.0115	.333	1.036	.036
0.90	.0394	.044	.438	1.11	.11
0.80	.098	.123	.613	1.25	.25
0.70	.167	.238	.738	1.47	.47
0.60	.219	.365	.865	1.73	.73
0.50	.250	.500	1.000	2.00	1.00

Although, the ratio of the velocities of the front of the wave for the two cases are not very sensitive to the transformation for H2 greater than 0.90, the differences are large for H2 near 0.5. However, the comparison made in this table is for flows with the same value for H2; if we compare flows with the same value for the volumetric flow rate of the source, i.e., for U′ = U, the velocity difference ratio, (vf′-vf)/vf is decreased. A few comparisons of this type are made in Table 4 in which the solution for the standard problem is listed as the upper line in each pair of data. For flow rates corresponding to values of U less than 0.05, the influence of the position at which material is withdrawn from the hall is small.

TABLE 4. Parameters for U′ = U and F2′ = 0

$u/\sqrt{g'ho^3}$ or $u'/\sqrt{g'ho^3}$	H2 h2/ho	Ff′ $vf'/\sqrt{g'ho}$	$\left(\frac{vf'-vf}{vf}\right)$
U = .044	0.89	.408	
U′ = .044	0.90	.438	0.07
U = .123	0.76	.500	
U′ = .123	0.80	.613	0.23
U = .238	0.55	.500	
U′ = .238	0.70	.738	0.48

4. Effects of Mixing at the Front and of Viscosity

The effects of mixing between the current and ambient fluid at the hydraulic jump or bore and the effects of viscosity are ignored in the analysis discussed above. Experimental data concerning these effects is briefly reviewed here.

(i) Mixing at the Front

Note that in these calculations, no mixing is allowed in the hydraulic jump or bore so that a precise comparison with the velocity of the front determined in experiments is not possible. When fluid is lost from the head, the velocity of the current must be larger than that in the head to supply this loss. Simpson and Britter were able to measure this difference. They found that the velocity in the front v_f is only slightly smaller than that of the current v and that the ratio of the two is approximately given by:

$$(v_f/v) = 1/(1.16 \pm 0.04) \qquad (15)$$

Because the two velocities are so nearly equal, we believe that values of the velocity of the current made for the inviscid case can be used as a first approximation to the velocity of the front or current when viscous effects are negligible.

The results expressed in equation 15 are also interesting because they contain information on the flow of gas into the mixed region. The magnitude of the velocity ratio indicates that there is a net flow of material from the current into the head and that this flow is then entrained from the head into the mixing layer shown in Figure 2. The net flow into and out of the head is about 16% of the flow in the current. This result is important to us since this means that 16% of the flow in the current mixes with and contaminates the ambient fluid.

(ii) Transition to Viscous Regime

Transition between inertial and viscous regimes occurs because of either the effect of viscosity on the flow over the front or because the displacement thickness of the boundary layer between the current and the wall grows to a value which is an appreciable fraction of the depth of the current. Simpson and Britter (1979) found that viscous effects on the flow over the front of the current were negligible when the Reynolds number for the front, based on layer depth and front velocity are greater than 500. We will be interested in this regime.

However, regardless of the Reynolds number for the front, the influence of the boundary layer will always appear if the front runs out far enough from the source. The viscous forces acting on the fluid at the wall will act to reduce the momentum of the flow and when the flow is long enough this force must have an effect on the motion of the front. The layer thickness at the source will grow so that the additional gravitational head at the source will be able to overcome the shear at the wall.

To make a simple estimate of the scaling laws for this transition, we examine the magnitude of the ratio of the boundary layer displacement thickness to the depth of the gravity current. When this ratio is very small, the influence of the the boundary layer is presumably negligible and when it reaches some limiting value, viscous effects will become important.

When the boundary layer between the current and the wall is laminar, we can make an estimate for the transition position by examining the ratio of viscous shear forces on the wall to the momentum flux in the layer at the source,

$$(0.5\, \rho_c\, v^2\, X\, Cf)/(\rho_c\, uv)$$

or the ratio of the displacement thickness δ to the original layer thickness, (δ/h),

$$\delta/h \propto (X/h)/\sqrt{(Xv/\nu)}$$

These ratios grow as the distance to the front, X, increases and when either reaches some small limiting value, we expect that the influence of viscous forces will become important.

Thus if we assume that the transition occurs when this ratio takes on some limiting value, we find by using either ratio that the transition length scales as:

$$X_t \propto vh^2/\nu$$

or

$$Re)_t = X_t v/\nu \propto (u/\nu)^2 \qquad (16)$$

When U is so small that the velocity of the current is given by v)o, equation (13), the dependence on the height of the channel is unimportant and the criterion becomes:

$$X \propto \sqrt{g'h}\, h^2/\nu \qquad (17)$$

Estimates of the position at which this viscous effect becomes important have been made by Chen et al (1976) and Chen (1980). Their experimental results agree with the form of equation 17 and the value of the proportionality constant was found experimentally to be about 0.10.

(iii) Viscous Regime:

In this regime, dimensional analysis and some experimental results, presented for example in Chen (1980), Chen and List (1976) and later by Didden and Maxworthy (1982), suggest that the velocity of the head of the current depends on the distance from the source of the front, X, and can be expressed as:

$$vf/((g'u^3/X\nu)^{1/4}) = j = (0.54) \qquad (18)$$

when U is so small that the duct height does not affect the velocity.

In this regime, the velocity of the front decreases with increasing X as X to the minus one fourth power and thus the depth of the current at the source must rise so that the gravitational forces can support the wall shear. The value of the constant j which appears in equation 18 gives a reasonable fit for a range of experiments.

5. Application of results for the subcritical source:

In many fire situations of interest, the flow will be entirely within the inertial regime and as a result the analysis presented above can be used to describe the flow.

As an example, consider the situation shown in the sketch of Figure 1 and let fires of various sizes be started in the small room adjacent to the hallway. Hot gas will flow from the room through the open door into a 2.5m square hallway and produce the hydraulic jump and gravity current shown in the sketches. Calculations have been made to show the properties of the ceiling currents produced by several fires and the results are shown in Table 5.

TABLE 5. EXAMPLES OF GRAVITY CURRENTS in a 2.5 m SQUARE HALL

EXAMPLE NUMBER:	#1	#2	#3	#4	#5	#6
1. PARAMETER VALUES ASSUMED:						
Fire size, kw:	50	50	50	200	200	800
Mass flux to current, kg/s :	0.5	1.0	2.0	1.5	3.0	3.0
2. PARAMETER VALUES CALCULATED:						
Temperature in current, C	120	70	45	153	86	285
flow rate in current u, m /s	0.22	0.39	0.72	0.73	1.23	1.90
density difference ratio, D	0.29	0.16	0.082	0.38	0.20	0.62
dimensionless flow rate, U	0.034	0.079	0.204	0.095	0.220	0.195
s, for steady regime; us, unsteady flow regime	s	s	us	s	us	us
dimen. current height, H	0.09	0.17	0.37	0.20	0.40	0.35
dimen. velocity of head, Ff	0.38	0.47	0.50	0.49	0.50	0.50
dimen. velocity of bore, Fb	-	-	0.34	-	0.39	0.37
height of current h, m	0.22	0.42	0.93	0.49	1.00	0.87
height of head m	-	-	1.25	-	1.25	1.25
velocity of front vf, m/s	1.01	0.92	0.71	1.49	1.12	1.95
velocity of current v, m/s	1.01	0.92	0.95	1.49	1.23	2.79

Based on fire plume entrainment work, e.g., see Cetegen et al (1983), values were picked for the mass flux in the fire plume and then in the gravity currents which form downstream of the hydraulic jump. Then given the mass flux and enthalpy flux in the ceiling current, which is equated to the fire size, the rest of the parameters can be easily found, with the use of Table 1, for the case that the velocity far upstream of the front is zero.

In all examples in this table, the Reynolds number of each flow based on current velocity and depth is greater than ten thousand and the transition length is greater than 1000 meters. Hence, the Reynolds number and transition position are large enough to ensure that the flow will be in the inertial regime, and the influence of viscosity on the geometry and the propagation speed of the front should be negligible.

Examples 1 to 3, and 4 and 5 show the effects on the parameters of changing the mass flow in the current while holding constant the enthalpy flux, called here the fire size. For both the 50 and 200 kw examples, the depth of the layer increase almost linearly with the mass flux and the velocity decreases slightly. The reduction in the velocity of the front is due in part to the offsetting effects of the decrease in the density difference ratio D and the increase in the layer depth h.

The head of the current in these examples would traverse a 50 m long hall in from 25 to 70 seconds. Because the return wave would take a similar period, the total period required for the returning wave to reach the jump will be from one to two minutes.

For the first example, the gravity current occupies about 9% of the height of the hall. The depth behind the reflected wave will be larger by about a factor of about 1.5 and hence, the depth of hot gas in the hall will be about 15% of the height of the hall when the reflected wave submerges the hydraulic jump and suppresses further entrainment into the current. Thus, a considerable fraction of the hall will be filled with hot gas before the special conditions requiring modelling of the gravity current can be relaxed. In the other five examples, this depth is much larger. Hence, for many fire situations, the process by which the hall is filled with hot gas will be dominated by the gravity current flow described here.

In all of these examples, the current depth is greater than 0.22 m or about 9 inches and it is possible that the current would set off sprinklers located within this distance below the ceiling. Two of the examples produce gravity currents in the Unsteady Flow Regime and have a depth near the head of the current equal to one half of the hall height. Most of these flows would be threatening to a five foot high person (1.5 m or 60% of the hall height) standing or running within the hall although the velocity of the front, 0.7 to 1.5 m/s, would not be hard for an alert, healthy person to outrun.

The weakness of the discussion given here is that we have assumed values for the mass flow rate in the currents described in Table 5. In a later report we will describe the flow in the hydraulic jump at the entrance of the hall and a technique for matching the flow in the jump with that in the current. For the situations in which this jump is important, we will then be able to give a more complete picture for the flow.

C. CURRENT SALT WATER MODELING WORK

In our investigation, the salt-water modeling work will be used to obtain both a qualitative and where possible a quantitative picture of the flow for a number of fluid dynamic problem areas and will act as a guide for the gas phase experiments. Because of the ease in making flow visualization experiments, this technique is particularly useful in making a survey of new problem areas.

The standard problem to be investigated is that of a gravity current flowing steadily into a long hallway in which the ambient fluid is initially at rest. The source will be subcritical, as illustrated in Figure 1, and the Reynolds numbers will be high enough to keep the flow within the Inertial Regime. Both ends of the hall will be closed and the ambient fluid will be withdrawn from the end of the hall at which the current is introduced.

A number of important variations on the basic flow will also be investigated. An important experimental condition for these studies is the origin for the ceiling current. We plan to start the studies listed below with a subcritical source which leads to a current as shown in Figure 1c and 1d, and later will investigate some of the flows arising from the two other types of sources discussed above: one, which simulate a buoyant plume above a fire, Figure 3c, and a second which will be the supercritical source which has considerable momentum at the inlet and which will lead to conditions indicated in Figure 3a or 3b.

A second condition concerns the flow rate of the buoyant fluid. In a fire situation we expect that the flow rate of this fluid can change substantially even over the brief period during which the gravity current will be flowing down a long hall. The influence of this nonsteady supply will be investigated.

A third condition concerns the motion of the ambient, high density gas within the space. In most of the above discussion this fluid was at rest or was moving in response to the motion of the gravity current. In some fire situations, the high density fluid will be in motion due to a variety of causes. If the flow is against the direction of flow of the gravity current, the current can be stopped completely and the mixing between the current and ambient fluid will be different from that which exists when the ambient fluid is stationary. Thus, the point at which the ambient fluid is withdrawn from the hall and the presence of flow in the ambient gas produced by an imposed pressure field must also be investigated.

1. Problem Areas

Problem Areas to be studied with the salt-water/water modeling method include:

(i) For the standard subcritical-inlet problem, the determination of the dependence of the velocity of the front and the current depth, relative to hallway height, on the parameters of the system such as volumetric flow rate, density difference ratio, the Reynolds number of the flow, and point of withdrawal of ambient fluid. We hope to check previous work here, rather than to break new ground, and to verify that our technique is correct.

(ii) The determination of the rates of mixing between gravity current and ambient fluid which occurs near the front of the current. Previous work suggests that in the high Reynolds number regime about 16% of the injected material is mixed with ambient fluid at the head of the flow. Again we want to check this result and to make sure that it is applicable to our problem. A quantitative measure of the concentration in the mixed layer will be made.

(iii) The interaction of the gravity current with (a) a closed end on the hall, (b) with a partially open end, and (c) with a right angle turn in the hall. As a part of this work we will determine the velocity of propagation of the reflected wave which is formed, at the interface between the current and ambient fluid, by these impingement processes.

(iv) The determination of the effect of rapidly changing the flow rate of hot gas which is supplied to the ceiling layer on the development of the layer and the mixing between the layer and ambient fluid.

(v) The effect on the flow of (a) roughness elements placed on the ceiling of the hall, with a range of roughness element heights ranging from a few percent to 10% of the hallway height, and (b) systematic variations in the width of the hall, such as result from inset doorways located in hotel corridors, with a variation in width of 10 to 20% of the hallway width.

(vi) The effect on the flow produced by the gravity current of the presence of a stratified layer of hot gas in the hallway before the introduction of the gravity current.

(vii) The effect on the flow and in particular on the mixing between the gravity current and the ambient fluid of turbulent velocity fluctuations of appreciable amplitude in the source flow for the current.

(viii) The effect on the flow of the location of the point at which fresh water is withdrawn from the duct and of a flow in the ambient fluid either opposing or aiding the motion of the gravity current.

In addition to these subjects which deal with the motion of the front we are interested in two other problem areas:

(ix) The rate of entrainment of ambient fluid into the current which occurs in the initial hydraulic jump described in Figure 1.

(x) The motion of waves produced by the impact of the current on the wall of the hallway and other disturbances in the hall.

2. Preliminary Experimental Results:

Preliminary experiments have been made in which we have recorded on video tapes the motion of gravity currents formed when dyed salt water (density in the range 1.04 to 1.10) is introduced into a duct which is filled with fresh water (density 1.00). The duct is 15cm square and 240 cm long, and thus has a length to height ratio of about 16. Some of the results obtained in these preliminary experiments are summarized below. In these tests, fresh water is withdrawn from the hallway at the end of the duct where the salt-water flow enters.

Preliminary observations are presented in the following paragraphs.

(i) The velocity of the front as measured in our experiment is less than the values we expected from a review of previous work presented above. The differences, between our data and the values predicted from inviscid theory, range from 50% at low flow rates, and hence small Reynolds numbers, to 20% at high flow rates, and hence higher Reynolds numbers. The difference may be due to the mixing process and to the development of the boundary layer, formed between the wall and the current, and the mixing layer, formed between the current and the ambient flow, which are ignored in the theory.

We are investigating the cause for this difference and are also reviewing data from a number of different authors whose normalized velocity data appear to lie between our results and the theoretical values. Of course, the effects of boundary layer growth will be more important in these small scale experiments than in the full scale case.

(ii) Visual inspection of the flow indicates that mixing between the gravity current and ambient fluid occurs only at the head of the current and nowhere else in the flow. The mixing appears to involve a small amount of the fluid from the current and a much larger amount from the ambient flow.

(iii) The velocity of the front decreases slightly when the head reaches a point several hall heights in front of the end wall of the duct. On impact, the front rides "down" the wall (see Figure 7a and 7b) and additional mixing does occur but, for the Reynolds number range we have investigated, it is very small and is restricted to the impact event.

(iv) After the current reaches the wall at the end of the hall, it is reflected as a series of waves which propagate from the closed end toward the source end of the duct, Figure 7c and 7d. The reflected waves have wave lengths of several hall heights; they do not "break" or cause any mixing; and they propagate at a roughly constant velocity toward the source of the current with a velocity which can be larger than that of the head of the current. The thickness of the layer behind the wave train is about 1.5 to 2 times that of the current in front of it.

(v) If a gravity current is introduced into a hallway which contains a thin stratified layer of fluid with density close to that in the gravity current, the head of the gravity current becomes a wave superimposed on the existing stratified layer. Depending on the depth of the layer in the hall and the density difference ratio, the wave at the head of the gravity current may or may not break and its velocity may be reduced as compared to a similar current moving in a hall without the stratified layer. When the wave does not break, no mixing occurs at the head of the wave. Wood and Simpson (1984) have studied this phenomena.

Similarly, increasing the flow supplied to a gravity current which has started to move down a hall need not produce a second breaking front but can cause a non-breaking wave to propagate through the gravity current toward the front.

(vi) The interaction of the current with an obstacle placed on the ceiling, a square "beam" occupying about 12.5% of the height of the duct has been observed visually. The complete flow field produced by the interaction of the front with the obstacle is complex, and produces a flow which follows the description given in Figure 1 when the beam replaces the door soffit. The supercritical region and the hydraulic jump were observed to form just downstream of the beam and the jump was swamped by the reflected waves, as suggested in the Figure 1.

3. Implications for Modeling

These preliminary results suggest that:

(i) The scaling laws for transition and velocity described above are at least roughly applicable to our problem and the velocity of the front except for very thin layers will be in the range 0.5 to 2 m/s. Thus the time required for the front to flow down a hallway will be in the range of tens of seconds.

(ii) Mass lost by entrainment from the current and into the ambient gas occurs at the head of the current and is probably less than 15% of the injected flow. Thus, to a first approximation, we may be able to ignore it entirely in a simple room-fire model.

However, entrainment of ambient fluid into the current at a hydraulic jump, for example that produced by flow over a door soffit as shown in Figure 1, can be large compared to the flow in the current supplied to the room and hence must be modeled carefully.

Thus, details of the flow which lead to the production of the current, such as the entry of the current into the room shown in Figure 1, appear to be very important.

(iii) Once the current has reached the end of the hall, the motion at the interface between hot and cold fluid is that of a stratified layer disturbed by interfacial waves which do not produce additional mixing.

After the reflected wave has returned to submerge the hydraulic jump, see the example described in Figure 1, further mixing due to the gravity current can be ignored and the two-layer fire model used as usual.

(iv) Salt-water/water experiments will give us valuable insights into the flow processes without necessarily giving us quantitative results. A major problem here is to get Reynolds numbers high enough to ensure that the process is independent of viscous effects.

These results suggest that to a first approximation we were correct in ignoring entirely the lateral motion of gas in large rooms in the context of the two layer fire models.

However, for long hallways the time required for the current to traverse the space, and the effects of entrainment into the current and certainly of heat transfer will not be so easily dismissed and must be included in room-fire models.

In addition, the results described above were obtained with flows for which the Reynolds numbers, based on speed of the front and layer thickness, were in the range from 200 to 1000. Real flows of interest to us have Reynolds numbers about ten times larger than these values and these preliminary experiments suggest that the mixing may increase markedly with Reynolds number in this range. Hence, the optimistic conclusion that we may be able to ignore the lateral motion of the gas may not be realistic for high Reynolds number flows. However, this attractive idea will be pursued in our work.

Given the importance of the Reynolds number here, one of our important experimental objectives is to greatly increase the range of Reynolds numbers we can investigate in the salt-water modeling apparatus.

D. EXPERIMENTAL PROGRAM FOR GAS MODELING WORK

The experimental study of gravity currents in gasses will be used primarily to determine the influence of heat transfer on gravity currents. However, the duct has been designed to have about the same range of Reynolds numbers as the salt-water/water modeling apparatus and the other flow parameters can also be duplicated in the two experiments. Many of the problems mentioned above can be studied in both and, where ever possible, we will attempt to use the gas apparatus to verify novel findings discovered in salt-water/water modeling work.

The heat transfer studies will be carried out in an apparatus which is a model for a hallway. The dimensions of the duct are 50 cm square, 735 cm long, and a length to height ratio of about 14.5. This duct has glass side walls to allow flow visualization and reduce lateral heat transfer, a wooden floor to facilitate the insertion of instrumentation, and an aluminum top wall which is 1.27 cm (0.5 inches) thick. The height to width ratio for the duct can be easily changed so that the influence of aspect ratio can be studied.

Aluminum was selected for the top wall for the initial tests because it has sufficient thermal capacity and a large enough thermal conductivity to keep the surface temperature within a few tenths of a degree of the initial value during the transient test. This constant temperature boundary condition will greatly facilitate data reduction and the development of a good model for the flow. The apparatus is designed so that walls with other thermal properties can be studied easily.

Heat transfer gauges are located at 50 cm intervals on the centerline of the ceiling and at 150 cm intervals several can be placed across the width of the ceiling. A shadowgraph system is being developed as our principal flow visualization technique. Velocity and temperature distributions in the gravity current will be measured at one or two locations in each experiment with 5 to 10 hot wire probes mounted on a single support.

Both velocity and temperature will be measured from the same wire. The chief challenge which arises in the design of this probe is to make accurate measurements of either temperature or velocity at the very low gas speeds we anticipate will be present in the gravity currents.

The support for the velocity and temperature probe is designed so that the probe can to be moved easily throughout the duct between experiments; however, to cover a given flow throughout the whole duct will require that a number of separate but identical experiments be carried out.

Hot gas at temperatures up to 250 C will be supplied at a closed end of the duct at a known volumetric flow rate, and the motion of the front, the velocity and temperature distribution behind the front and the heat transfer to the ceiling will be measured. The initial tests will investigate the transient flow produced with an open end on the hall; later work will include the study of the reflected wave from a closed or partially closed end. The parameters to be investigated include: current temperature and volume flow rate, end condition on the hall (i.e., open, closed and etc.) thermal properties of the ceiling, width to height ratio of the hall, and the presence of roughness on ceiling and side walls.

The duct has been constructed and the heat transfer instrumentation, installed for the initial experiments. At present, the heater for the hot gas supply is being tested. The hot wire probe apparatus is still under construction.

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LIST OF SYMBOLS

The meanings for many of the symbols are illustrated in the sketches of Figures 2 and 4.

a,c,j, constants in equations

b, the hall width

D, the density difference ratio, $(\rho_a - \rho_c)/(\rho_a)$

Cf, skin friction coefficient

g, the gravitational acceleration, 9.8 m/s

g′, the reduced gravitational constant, g′ = Dg

F, the current flow rate parameter, $v/\sqrt{g'ho}$

Fi, flow rate parameter, $vi/\sqrt{g'ho}$, note that various values for i are defined below

ho, the duct height

h, the current height near the source see Figures 2 and 4

h2, the depth of ambient fluid beneath the source, i.e., ho-h2; see Figure 2 and 4

hh, the height of the head above the current, see Figure 2

H2, the dimensionless depth of ambient fluid beneath the source, h2/ho

u, the volumetric flow rate per unit width of the hall supplied by the source, i.e., u = V/b , with units, m^2/s

U, the dimensionless value for the volumetric flow rate per unit width of the hall supplied by the source, i.e., $U = V/b\sqrt{g'ho^3}$

V, the normalized current speed based on the current depth, $v/\sqrt{g'h}$, rather than on the depth of the duct, ho

$\dot{V}$, the volumetric flow rate supplied by the source

v, the velocity of the flow in the current in the constant height region behind the bore, coordinates fixed in the wall, see Figure 4 vb, the velocity of bore or hydraulic jump, coordinates fixed in wall.

vf, the velocity of front or head, coordinates fixed in wall

vw, the velocity of the wave reflected from wall of hall

vo, the velocity of the flow far upstream of the head of the current, coordinates fixed in the wall

X, distance front has moved downstream of source

X , distance at which transition to viscous regime occurs

δ , displacement thickness of the boundary layer

ρ_c , the density of the fluid in the current

ρ_a , the density of the ambient fluid in the hallway

ν , the viscosity of the fluids (taken as being equal for both)

Subscripts:

f, front

b, bore

2, flow in ambient fluid below source

Superscripts

( )′, prime denotes parameter values in a coordinate system with arbitrary velocity, v2′, in the flow beneath the source See section IV.3.B.v.

TABLE I: PARAMETERS FOR GRAVITY CURRENT IN A HALLWAY

H2	F	Ff	Fb	U	H	V
h2/ho	$v/\sqrt{g'ho}$	$vf/\sqrt{g'ho}$	$vb/\sqrt{g'ho}$	$u/\sqrt{g'ho^{3}}$	h/ho	$v/\sqrt{g'h}$
0.50	0.500	0.500	0.207	0.2500	0.50	0.707
0.51	0.506	0.500	0.218	0.2478	0.49	0.723
0.52	0.511	0.500	0.228	0.2454	0.48	0.738
0.53	0.517	0.500	0.239	0.2428	0.47	0.754
0.54	0.522	0.500	0.249	0.2400	0.46	0.769
0.55	0.527	0.500	0.260	0.2370	0.45	0.785
0.56	0.531	0.500	0.270	0.2338	0.44	0.801
0.57	0.536	0.500	0.281	0.2303	0.43	0.817
0.58	0.540	0.500	0.291	0.2267	0.42	0.833
0.59	0.543	0.500	0.302	0.2228	0.41	0.849
0.60	0.547	0.500	0.312	0.2188	0.40	0.865
0.61	0.550	0.500	0.323	0.2145	0.39	0.881
0.62	0.553	0.500	0.333	0.2100	0.38	0.897
0.63	0.555	0.500	0.344	0.2053	0.37	0.912
0.64	0.557	0.500	0.354	0.2004	0.36	0.928
0.65	0.558	0.500	0.365	0.1953	0.35	0.943
0.66	0.559	0.500	0.375	0.1900	0.34	0.958
0.67	0.559	0.500	0.385	0.1845	0.33	0.973
0.68	0.559	0.500	0.396	0.1788	0.32	0.988
0.69	0.558	0.500	0.406	0.1728	0.31	1.001
0.70	0.556	0.500	0.417	0.1667	0.30	1.014
0.71	0.553	0.500	0.427	0.1604	0.29	1.027
0.72	0.549	0.500	0.437	0.1538	0.28	1.038
0.73	0.545	0.500	0.448	0.1471	0.27	1.048
0.74	0.539	0.500	0.458	0.1401	0.26	1.057
0.75	0.532	0.500	0.468	0.1329	0.25	1.064
0.76	0.523	0.500	0.479	0.1256	0.24	1.068
0.77	0.513	0.500	0.489	0.1180	0.23	1.070
0.78	0.501	0.500	0.499	0.1102	0.22	1.068
0.79	0.495	0.495	0.495	0.1040	0.21	1.081
0.80	0.490	0.490	0.490	0.0980	0.20	1.095
0.81	0.484	0.484	0.484	0.0919	0.19	1.110
0.82	0.477	0.477	0.477	0.0859	0.18	1.125
0.83	0.470	0.470	0.470	0.0799	0.17	1.139
0.84	0.462	0.462	0.462	0.0739	0.16	1.154
0.85	0.453	0.453	0.453	0.0679	0.15	1.169
0.86	0.443	0.443	0.443	0.0621	0.14	1.185
0.87	0.433	0.433	0.433	0.0562	0.13	1.200
0.88	0.421	0.421	0.421	0.0505	0.12	1.215
0.89	0.408	0.408	0.408	0.0449	0.11	1.231
0.90	0.394	0.394	0.394	0.0394	0.10	1.247
0.91	0.379	0.379	0.379	0.0341	0.09	1.263
0.92	0.362	0.362	0.362	0.0289	0.08	1.279
0.93	0.343	0.343	0.343	0.0240	0.07	1.295
0.94	0.321	0.321	0.321	0.0193	0.06	1.312
0.95	0.297	0.297	0.297	0.0149	0.05	1.328
0.96	0.269	0.269	0.269	0.0108	0.04	1.345
0.97	0.236	0.236	0.236	0.0071	0.03	1.362
0.98	0.195	0.195	0.195	0.0039	0.02	1.379
0.99	0.140	0.140	0.140	0.0014	0.01	1.397
1.00	0.000	0.000	0.000	0.0000	0.00	1.414

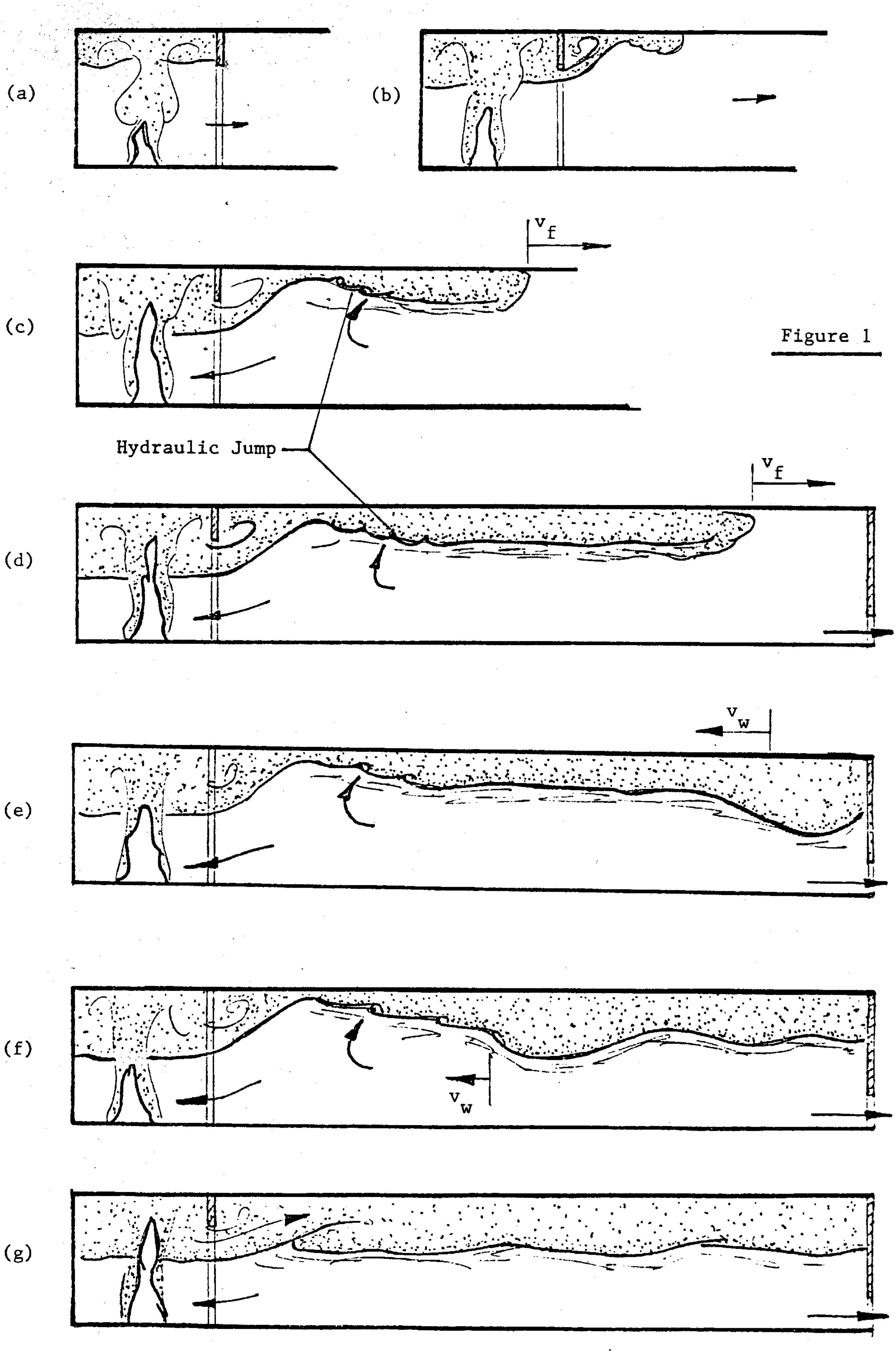


Figure 1

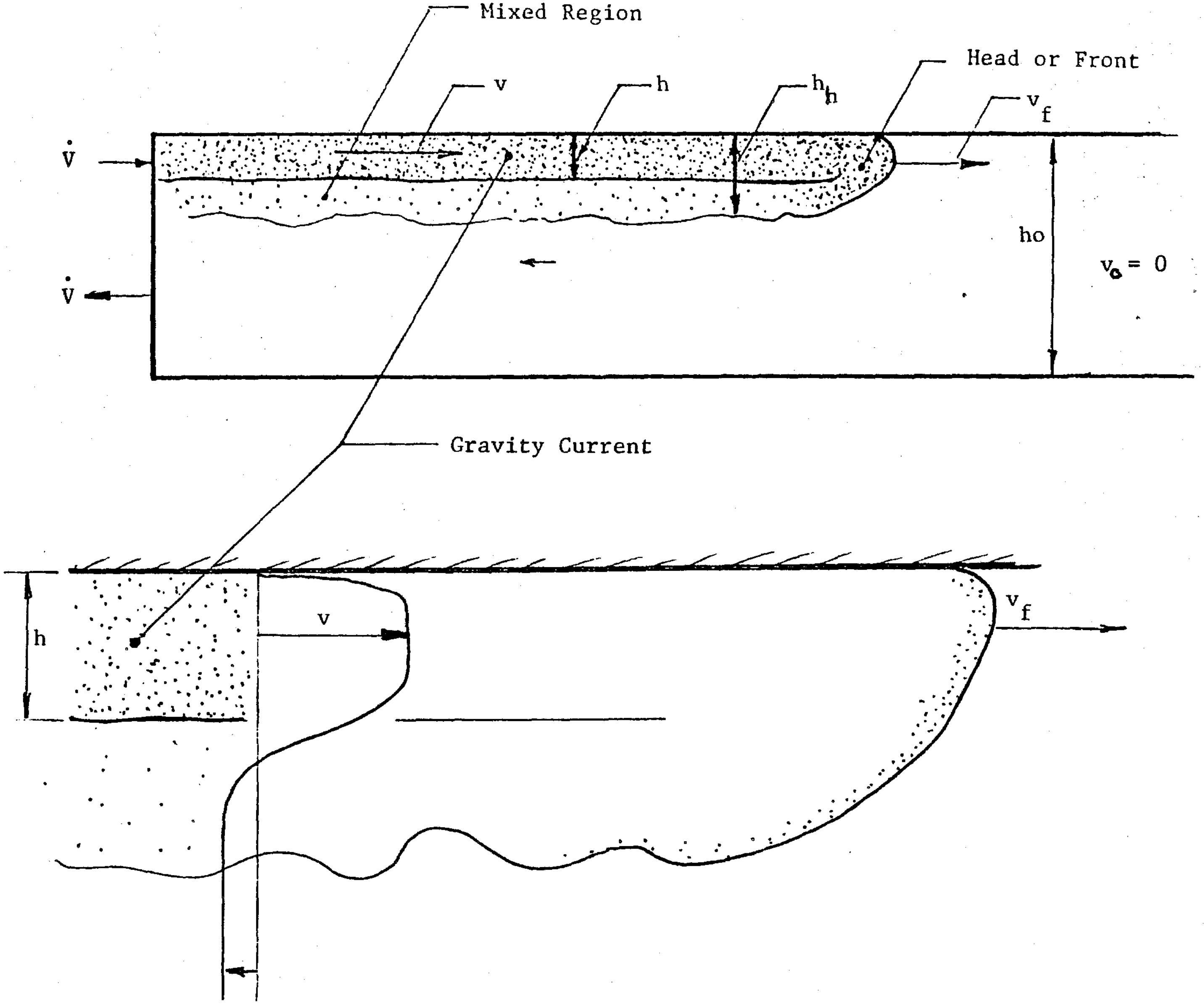


Figure 2. Subcritical Source

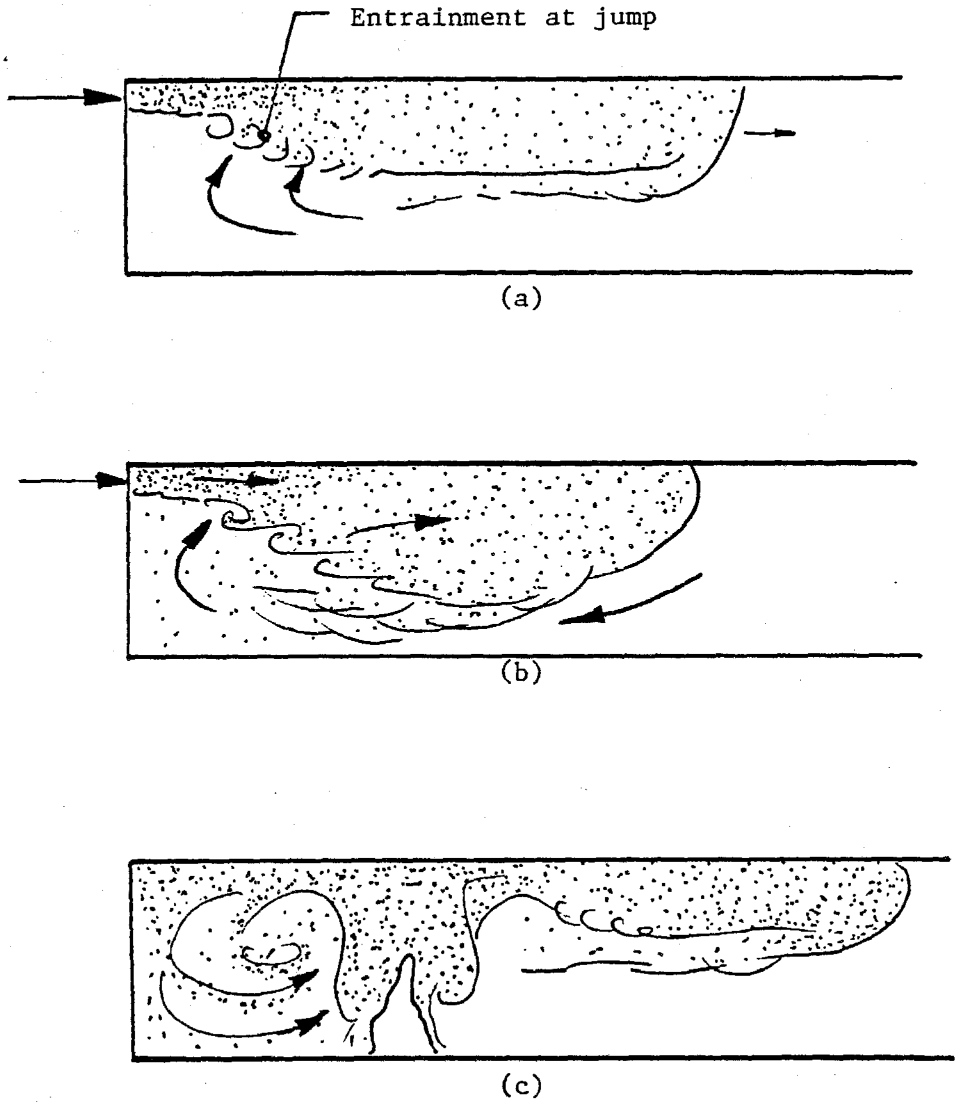


Figure 3. Alternate Sources

a. Supercritical Source
b. Supercritical Source with Secondary Mixing
c. Plume Source

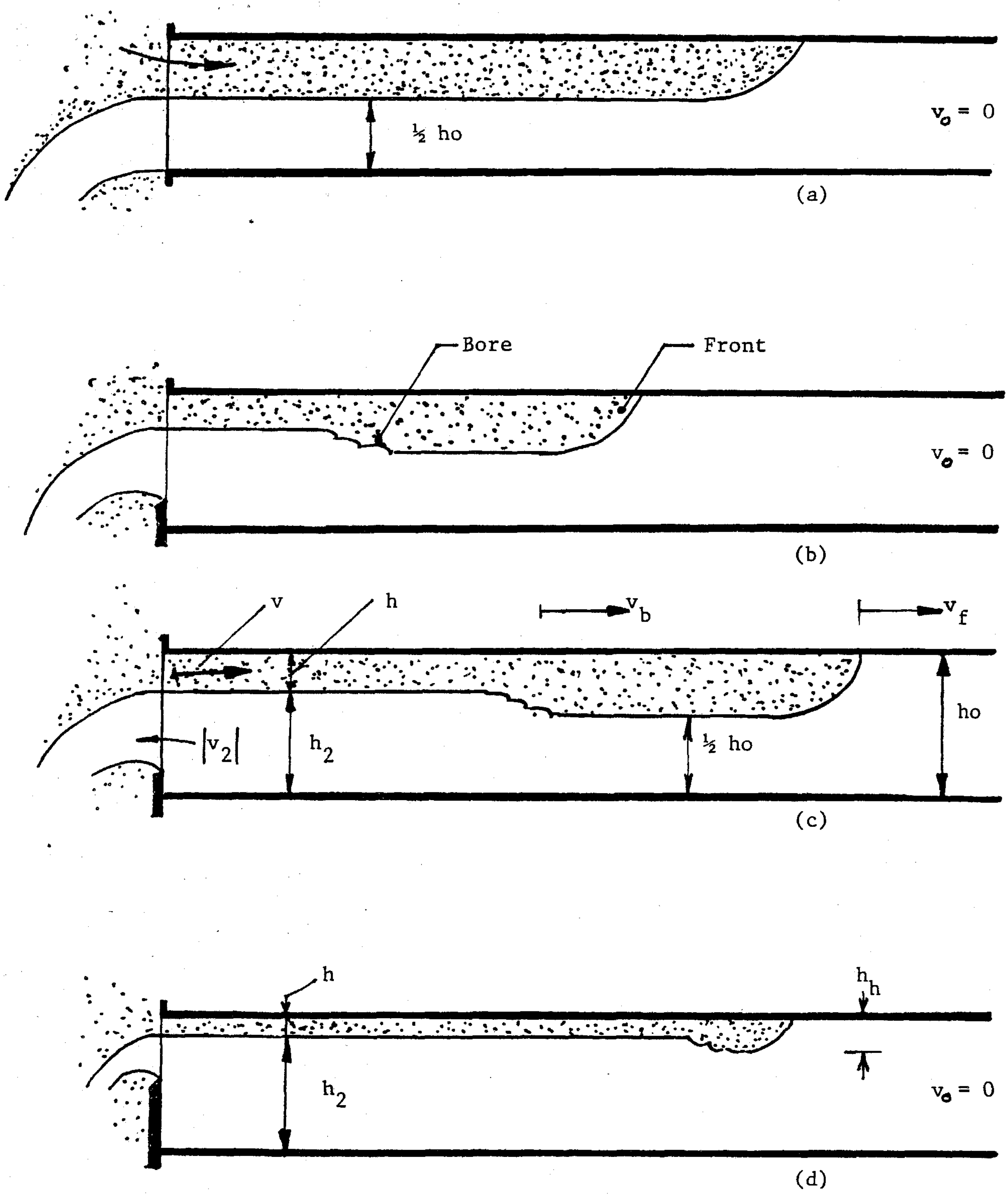


Figure 4. Flow Regimes: (a) Constant Energy; (b) + (c) Unsteady and (d) Steady Flow Regime

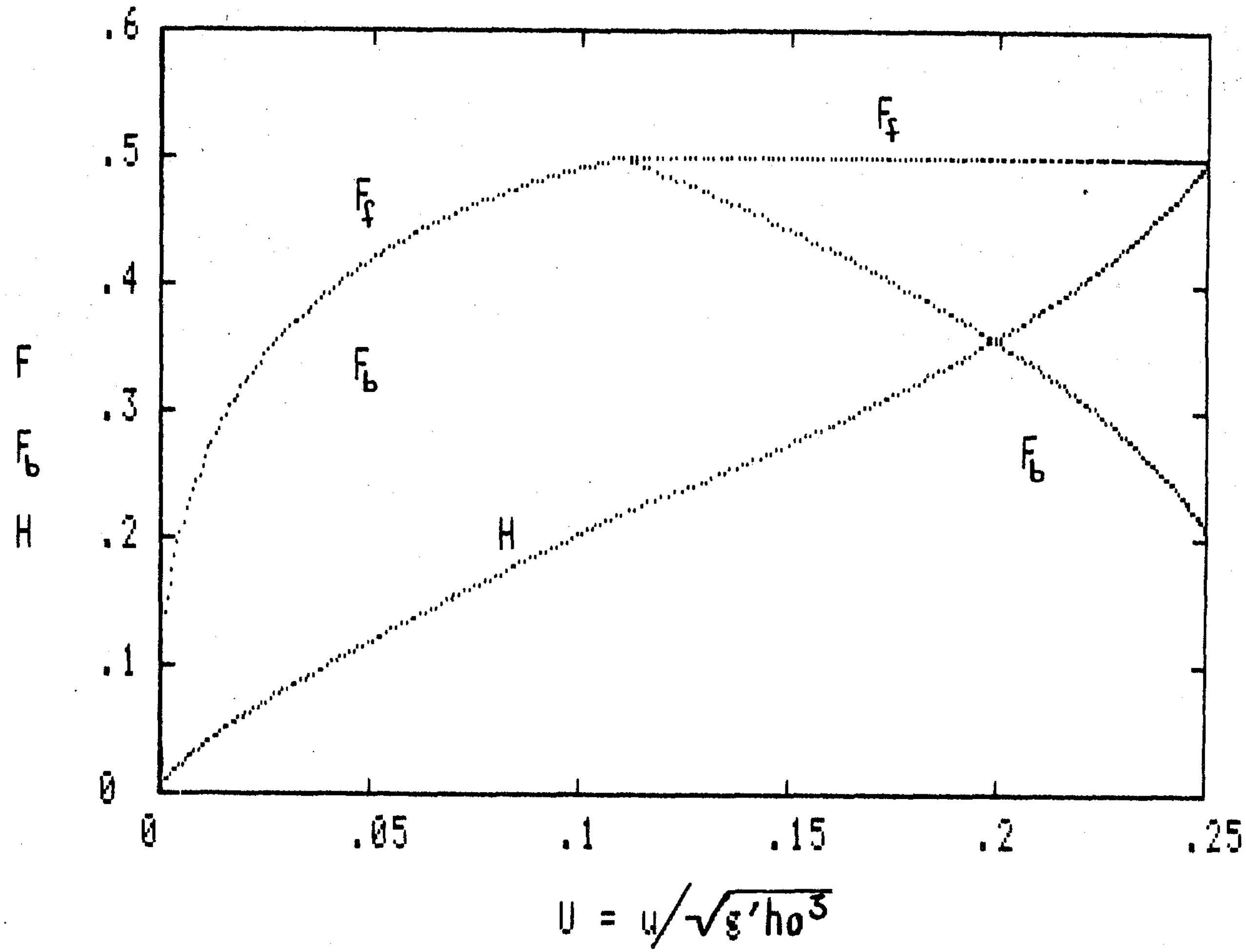
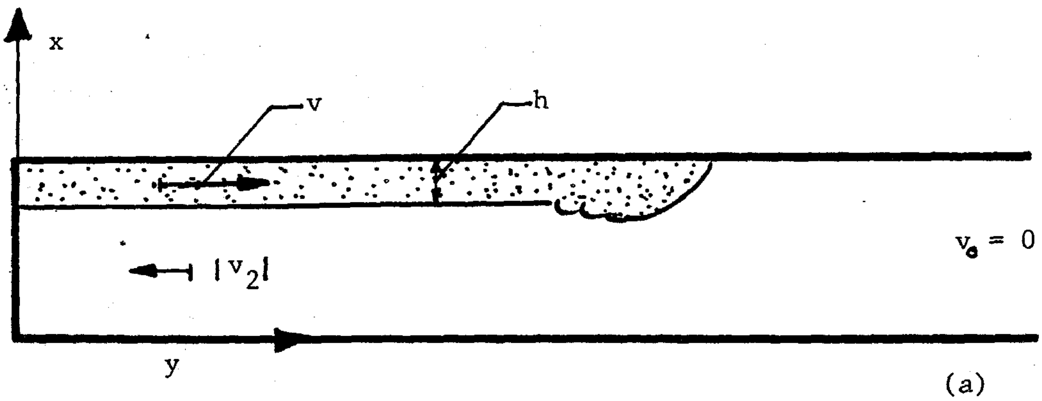
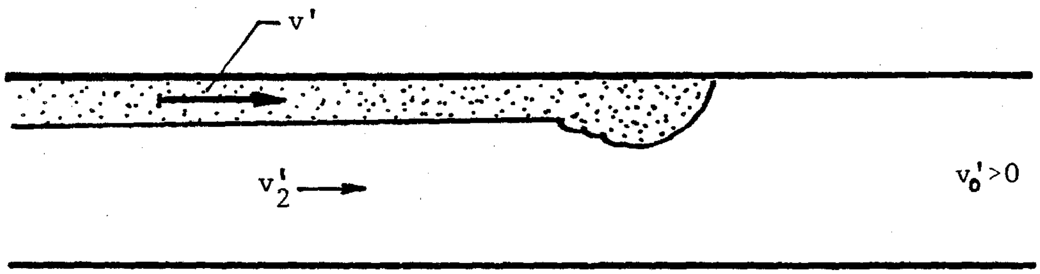


Figure 5. Inviscid Flow Parameters



(a)

$$hv = (ho - h)\ v_2$$



(b)

$$vo'ho = v'h + v_2'\ (ho - h)$$

Figure 6. Galilean Transformation

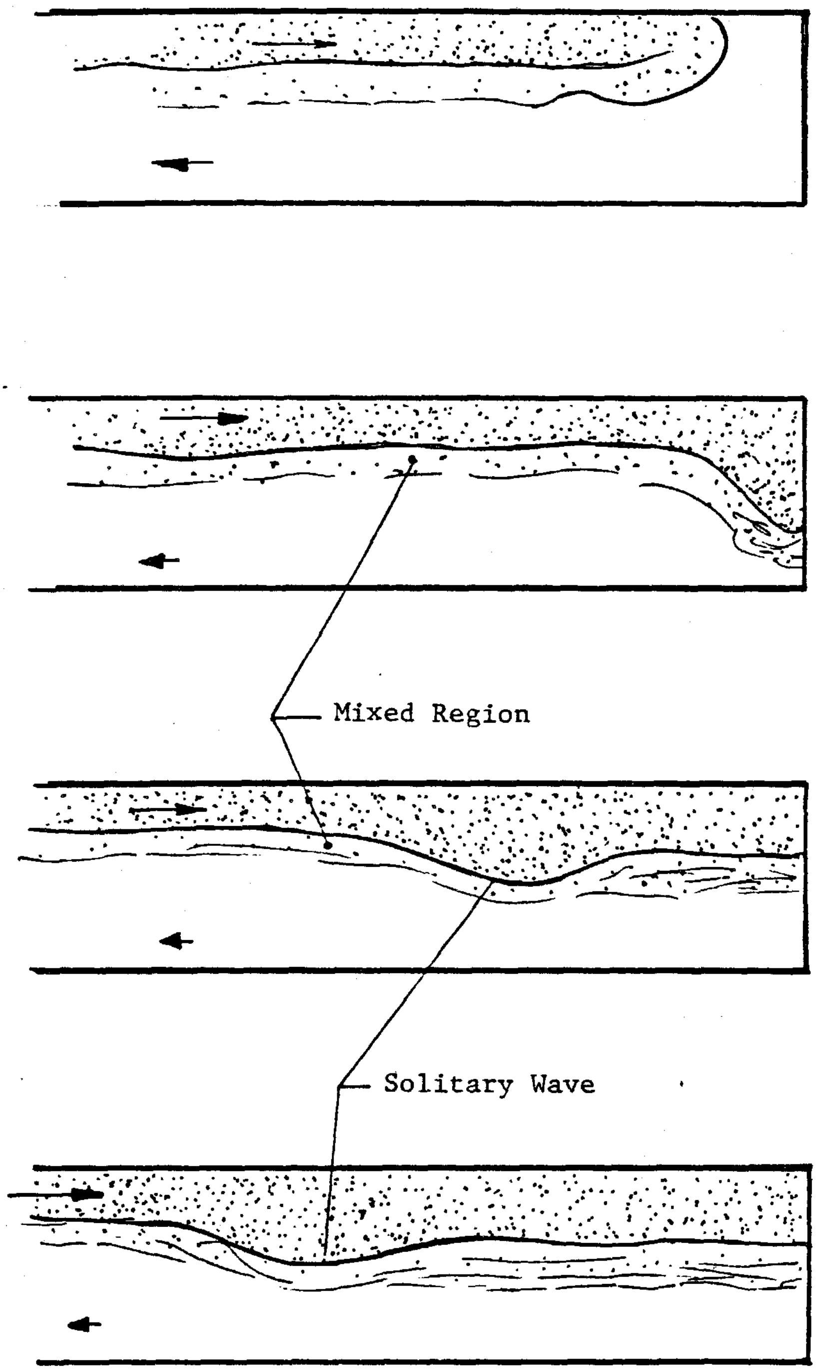


Figure 7. Impact on End Wall